Army Research Laboratory

The Effects of Slow Frame Rates on Human Performance

by Jennifer E. Thropp and Jessie Y.C. Chen

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The Effects of Slow Frame Rates on Human Performance

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14. ABSTRACT

We conducted a comprehensive examination of the effects of different frame rates on human performance and reviewed more than 50 studies and summarized them in the areas of psychomotor performance, perceptual performance, behavioral effects, and subjective perception. Overall, there seems to be strong support for a threshold of around 15 Hz for many tasks, including those that are psychomotor and perceptual in nature. Less impressive yet acceptable performance may be accomplished at around 10 Hz for many tasks. Subjective reactions to video quality seem to support rates of 5 Hz, although videos presented at 15 Hz and above are generally more widely preferred.

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1. Introduction

1.1 Background

In recent years, there have been growing applications of robotic technologies in fields such as space exploration, search and rescue, national defense, entertainment, police special weapons and tactics operations, health care, and personal assistance (Chen, Haas, Pillalamarri, & Jacobson, 2006). In the military domain, the U.S. Army's Future Combat System (FCS) program, for the first time in the U.S. military history, envisions a future battlefield incorporating a wide array of unmanned assets including aerial and ground vehicles as well as unmanned sensor platforms (Unit of Action Maneuver Battle Lab, 2003). These unmanned systems will extend the ranges and capabilities of their human operators' perception and action and will have a major impact on future combat operations (Oron-Gilad, Chen, & Hancock, 2005). In order to effectively employ the unmanned assets, it is essential that the robotic operator maintain an effective perception of the remote environment through the communication channel between the human operator and the robot. However, factors such as distance, obstacles, bandwidth, and electronic jamming may pose challenges for maintaining sufficient signal strength (French, Ghirardelli, & Swoboda, 2003). As a result, the quality of video feeds that a robotic operator relies on for remote perception may be degraded and the operator's performance may be compromised (Van Erp & Padmos, 2003).

Common forms of video degradation caused by low bandwidth include reduced frame rate (FR) (frames per second), reduced resolution of the display (pixels per frame), and a lower gray scale (number of levels of brightness or bits per frame) (Rastogi, 1996). The product of FR, resolution, and gray scale is bandwidth (bits per second), and it is important to determine how to balance these three variables with a given bandwidth so that operator performance can be optimized (Sheridan, 1992). Generally, for applications in virtual environments (VEs), many researchers recommend 10 Hz (i.e., 10 frames per second or 10 fps) to be the minimum FR to avoid performance degradation (Watson, Walker, Ribarsky, & Spaulding, 1998). However, depending on the nature of the tasks, the same degrees of slowing of FRs may have different effects on human performance. To provide a comprehensive examination of the effects of different FRs on human performance, this report reviewed more than 50 studies and summarized them in the areas of psychomotor performance, perceptual performance, behavioral effects, and subjective perception. First, some background information about the mechanisms of FR and other related sources of temporal distortions are presented. This discussion is followed by a brief review of the major moderating factors that can impact the adverse effects of slow FR on human performance.

1.1.1 The Mechanisms of FR

FR is the tempo at which the new frames of the graphical scene are computed, rendered, and displayed. Frame time (the length of time required to compute, render, and display the image), which is the inverse of FR, is the primary source of delay in desktop personal computers; in VEs, input devices such as three-dimensional (3-D) trackers are additional sources of delay (Watson, Walker, Woytiuk, & Ribarsky, 2003). FR is limited by several computational factors, including frame time, which is then determined by the current computational demands and the actual image displayed (i.e., complexity or level of detail [LOD]). Possible sources of low FR in VEs include the computation required to process tracker data (e.g., input from peripheral devices such as mice or eye trackers), computation speed of the effects of user movement (e.g., use of head-mounted displays [HMDs]), the graphical rendering time, and communication overhead in distributed systems. If any of these factors overwhelms the system or bandwidth limitations, the FR may be reduced. FR, however, is not an entity that exists in isolation; it is also associated with other computational demands.

1.1.2 Related Sources of Temporal Distortion

Bryson (1993) differentiates FR from lag, two major sources of temporal distortion in real-time computing systems. Lag is the temporal discrepancy between the data stream from the tracker (e.g., input device such as a mouse) and the actual resulting graphic (Bryson, 1993). Therefore, lag is the time delay between the user's action and its displayed result (Watson, Spaulding, Walker, & Ribarsky, 1997). In terms of teleoperation, delay is considered to be the temporal difference between communication between the local and remote sites (i.e., how long it takes for the user's command or input to see a result in the system's action) (Tharp, Liu, French, Lai, & Stark, 1992). Lag is also referred to as delay, latency, and system responsiveness (SR).

Lag is created by the following factors: delays in tracker signal, delays in communication between tracker and computer, delays from computations involved in processing tracker data, and delays from graphical rendering. SR resolution, however, can be complicated. SR is the combination of system latency (SL) and the time between the completion of the user's last action and the next source of input into the display. Furthermore, Watson et al. (1997) explain that frame time, SL, and SR vary randomly. SL is the frame time plus time needed for the system to collect input samples from the real world, such as tracker performance. The variation in latency is greater than the variation in frame time, and the variation in SR is the greatest, as it builds upon the variation in both frame time and SL. Thus, it is important to consider the means and the standard deviations of these display speeds.

Watson et al. (2003) maintain that there are several factors that cause delay in an interactive graphics system, some of which affect only frame time, while others impact only latency, and still others impact both frame time and latency. However, all these potential sources impact SR. Thus, FR and lag are closely related and are often manipulated at the same time (e.g., see Ware

& Balakrishnan, 1994). Bryson (1993) has stated that it is difficult to isolate the effects of lag and FR from other types of VE distortions. Watson et al. (1997) also state that lag is closely associated with FR and that they should both be considered by designers. However, there is not much research to guide these designers.

Latency and FR occur together but must be carefully manipulated in experiments in order for effects to be properly detected. Ellis, Adelstein, Baumeler, Jense, and Jacoby (1999) found that latency was a more reliable and stronger influence than FR on tracking performance in a VE. In a tracing task, latency was also more influential, having a multiplicative effect on response time (Arthur, Booth, & Ware, 1993). This may be because latency can be experimentally varied over a greater range than FR. For instance, in a study by Ellis et al. (1999), experimental latency ranged from 80 to 480 ms, yielding a proportion of 1:6, whereas the FR range of 6 to 20 fps yields a proportion of 1:3.7.

1.1.3 Update Rate and Refresh Rate

Update rate in teleoperation or in VE applications refers to the frequency at which the image of the remote site is captured and then displayed to the remote operator (e.g., via HMD or other displays), and it depends on the bandwidth limitation (Liu, Tharp, French, Lai, & Stark, 1993). Update rate, therefore, is the upper limit and determinant of display rate. For instance, if the FR of the HMD peaks at 100 Hz, and the update rate was 30 Hz, images could only be displayed at a maximum rate of 30 Hz. Usually, in the VE applications, FRs are higher than the update rates, so the image would appear smooth. In some VE literature, however, update rate and FR are sometimes used interchangeably (Kolasinski, 1995).

Refresh rate, on the other hand, refers to the number of images presented to the eye every second (usually between 60 and 10 Hz) (Richard, Birebent, Coiffet, Burden, Gomex, & Langrana, 1996). Basically, refresh rate is a hardware-determined constant, while update rate can vary widely based on scene complexity and other factors such as available computing power for generating the images (Kolasinski, 1995; Pausch, Crea, & Conway, 1992). The following example by Richard et al. helps to clarify the distinction between refresh rate and FR: a display system with a refresh rate of 60 Hz and an FR of 4 Hz will present 15 consecutive identical images before there are any changes in the scene.

Watson et al. (1998) state that high LOD in a frame's image and adequate SR facilitate user performance, yet make strong computational demands that often end in an LOD/SR trade-off. Update rate is directly proportional to bandwidth and is impacted by factors such as computation and rendering speeds of the graphics system. Thus, update rate could be increased if scenes were generated with simpler components such as lines and bioptic images as opposed to polygons and stereo images (Liu et al., 1993). Cai (2004) describes the merit of context-aware displays, in which the human user's perceptual state (e.g., user's scanning behavior with context anticipation) and the actual display content are monitored in order to provide the optimum LOD

for that specific image. This is an important consideration since human visual search can be guided by content and purpose (Yarbus, 1967), and excessive LOD can be minimized when not needed in order to allocate bandwidth to other demands, such as higher FR. In terms of temporal resolution, Cai (2004) found that when video was presented at less than 4 Hz, bandwidth usage was clearly lower than continuous streaming at approximately 17 Hz.

1.1.4 Variable Versus Constant FR

Many bandwidth studies have empirically manipulated constant FRs. Yet the amplitude and deviation of FRs can vary in a computing system, ultimately yielding a variable FR which may be reported as a range or mean. This variability can occur in presentations with significant change in the detail between scenes in the frames. Normally, in VEs, an adaptive detail management system adjusts the object polygon count from frame to frame, depending on the LOD needed, and consequently, this determines the frame update rate in order to present an approximately constant polygon count in each scene. However, when the LOD changes dramatically between frames, an adaptive detail management system may initially calculate the timing of the next frame erroneously.

Fluctuations in the actual frame times occur even when a specific FR is sought in a controlled environment. In other words, a particular FR can actually be a range of FRs, which yields a mean FR along with standard deviations in frame time. For instance, Watson et al. (1997) used the experimental stimuli presented for a 100-ms frame time and introduced a standard deviation in frame time of 20 ms, which in turn generated a range of frame times of 72 to 129 ms (the inverse of which corresponds to a range of FRs of 13.9 to 7.8 Hz). The implementation of frame time standard deviations can replicate the reality that numerous mechanisms result in a variable rather than constant FR in video transmission. Procedures for calculating variable FR values are presented in detail in Watson et al. (1997).

1.2 Adverse Effects of FR on Task Performance

Extremely low update rates can be problematic. As the FR becomes lower, the time (lag) between frames becomes longer, and the scene may appear jittery. Objects may consequently appear to move in saccades, and the human visual system has to conduct spatiotemporal interpolation to “fill” these visual gaps (Richard et al., 1996). Arthur et al. (1993) state that frame update rate and the lag in receiving and processing tracker data are among the two factors that are often associated with human performance in virtual worlds. Head-coupled tracking involves tracking head movements so that when the user moves his or her head, the perspective generated on the display will mimic real-life changes in perspective from head movements. Arthur et al. state that FR is directly related to a specific type of head-coupled display system lag in which there is a delay between eye position reception and display update. This is the time to compute and render a scene from the user’s perspective, since current tracker measurements are needed; two are needed if the display is stereoscopic.

Tharp et al. (1992) and Liu et al. (1993) state that 3-D tracking and “pick-and-place” tasks are two skills that are often required for tele-manipulation. Reddy (1997) explains that poor FR and large delay can degrade human-system interaction, often in terms of impaired depth perception on the visual display. Thus, the use of low FRs can have adverse effects on tele-manipulation, especially as far as depth perception is concerned. However, there are several moderating factors that might impact the adverse effects of low FRs. In this section, we briefly review five of those moderators: task dependency, viewing condition dependency, display luminance and the number of gray scale levels (GL), auditory cues in addition to visual cues, and end user characteristics.

1.2.1 Task Dependency

Johnson and Caird (1996), who investigated the impact of FR on sign language gesture recognition, remind readers that the required FR for performance of a task can depend on the nature of the task itself. If animation must be conveyed, then considering that the human visual systems takes 50 msec to process a frame, 20 Hz may be required (Card, Moran, & Newell, 1983). However, conveying a basic understanding of a sequence may require fewer frames.

It has been reported that 10 Hz is the minimum threshold for performance in immersive VEs (see Bryson, 1993; MacKenzie & Ware, 1993; Watson et al., 1997, 1998). However, higher rates of 10 to 15 Hz are required for acceptable performance (McKenna & Zeltzer, 1992). For architectural walk-through tasks, various minimum FRs have been recommended, including 6 Hz (Airey, Rohlf, & Brooks, 1990), 7 Hz (Pausch, 1991), and 10 Hz (Bryson, 1993; Card, Robertson, & MacKinlay, 1991; McKenna & Zeltzer, 1992).

Watson et al. (2003) differentiate between open and closed loop tasks, each of which is affected by FR. In a closed loop task, such as tracking, continuous feedback is provided. Thus, the result of the previous action feeds into the next action. Continuous feedback is therefore required for the operator to execute the next move. Automobile driving is considered to be a closed loop tracking task because the driver is required to maintain position of the vehicle within the specified lanes and to follow a prescribed pathway. In a tracking task, delay increases the time that passes until feedback is received by the user, and as a result, performance can degrade. Difficult tracking tasks are further impaired by delays.

Open loop tasks, on the other hand, have little or no feedback available to the operator. For example, placement task performance depends on predictive planning and is not guided by adjustments of feedback as are closed loop tracking tasks. However, placement tasks end in a closed loop phase where finer adjustments are made to place the object in its final position, which is a small target space.

1.2.2 Viewing Condition Dependency

Parkhurst and Niebur (2001) demonstrate the human observer's different needs of visual detail for different viewing conditions. In a *velocity-based* LOD graphics rendering technique, objects remain stationary but appear as a blur in the observer's visual field if he or she turns his or her head. Therefore, the blurred object does not need to have a high LOD. Thus, LOD is reduced as the object moves across the visual field but then increases again as the observer slows and stops his or her viewpoint rotation. In this rendering method, LOD is linearly related to rotational velocity of the observer. This method also keeps the system's computational load roughly constant.

In *distance-based* LOD manipulation (i.e., real-time viewpoint-dependent simplification), objects that are farther away from the viewer do not need to be rendered at high complexity. This reduction in detail then allows more resources to be allocated to the generation of higher FRs, as per the LOD-FR trade-off. There are other times when the human visual system does not naturally process high LOD, such as when objects are in the periphery of the visual field (Virsu & Rovamo, 1979) and when rapidly moving objects appear as blurred (Murphy, 1978; Burr & Ross, 1982).

Both pixel size and FR can influence the accuracy of perception of motion in depth. Even though the object may be moving at a constant velocity, this velocity appears to accelerate or decelerate, depending on whether it is located near or far from the viewer. According to Pfautz (2002), the motion of small objects near the line of sight and far from the viewer is likely to be limited by pixel size. However, the motion of large objects far from the line of sight and near the viewer is likely to be limited by FR. If FR and pixel size are correct, then the viewer can detect perspective depth.

There may also be differential effects for stereoscopic and monoscopic displays (see Arthur et al., 1993; Lion, 1993). In monoscopic displays, the image is presented to only one eye; in some settings, this can be done to avoid retinal image disparity. In stereoscopic displays, both eyes receive an image, but the image displayed to each eye is slightly different because of the position of the eyes relative to each other. Lion (1993) found that stereo performance was significantly better than mono performance in a manual tracking task. This was confirmed by Richard et al. (1996), who demonstrated that tracking task completion time was lower overall for the stereo condition.

There may also be effects for the use of head-coupled imagery on visual performance (see Lion, 1993). In restricted head coupling, participants rest their chins against a chin rest to control for the effects of parallax. This is another viewing condition variable which may be a moderator in the relationship between FR and human performance if both are manipulated simultaneously.

1.2.3 Display Luminance and the Number of GLs

The number of GLs is a characteristic of the video monitor and is usually measured in bits. Whiting, Honig, Carterette, and Eigler (1991) demonstrated a linear relationship between GL and video display luminance: in the range of 80 to 180 gl, there is a slope of 0.209 (candela [cd]/m^2)/GL. Whiting et al. were able to generate a mean luminance of 6.2 cd/m^2 (1.8 ft-lumen), which corresponds to a GL of 128. GL can also serve as a source of image noise; Whiting et al. manipulated pixel noise standard deviations of 5, 10, 14, and 20 GL for static images and 20 GL for dynamic noise. Also, image contrast can be defined as the GL increment of the target. Thus, GL could be a characteristic of visual display quality that could impact target detection performance independently as well as interactively with FR (also see Vitkovitch & Barber, 1994).

1.2.4 Auditory Cues in Addition to Visual Cues

It is also necessary to consider the influence of auditory components of visual presentations. In some settings, audition is thought to play a larger role in temporal perception than vision (e.g., see Welch, Duttonhurt, & Warren, 1986). For instance, musical tempo can influence the human perception of time in passing and display FR (Mastoropoulou & Chalmers, 2004; Mastoropoulou, Debattista, Chalmers, & Troscianco, 2005). Speech reading ability, which is rooted in target recognition, is significantly more accurate in audio-visual conditions than in an audio-only mode (Vitkovitch & Barber, 1994; Frowein et al., 1991). This effect may be a moderator that should be distinguished from possible FR manipulation effects.

Audiovisual skew or asynchrony between the video and the audio aspects of the image sequence can also affect recognition. It can be caused by low FRs that present obsolete visual information that does not match the continuous real-time delivery of sound. While this mismatch can typically impair performance, it can be helpful in some instances of low FR. For example, an asynchrony in which audio lags the visual component of the presentation can actually aid performance beyond that which can be normally perceived at 30 Hz (Knoche, deMeer, & Kirsh, 2005). The direction of audio-visual skew can be a moderator worth considering. Therefore, it is important to examine the full range of effects generated by an interaction among audition, vision, and FR.

1.2.5 End User Characteristics

Although many aspects of the system and experimental methods can influence the relationship between FR and performance, it is important to consider the individual differences in the humans who use these systems. One possible moderator is the level of experience the operator has with computers and virtual reality (VR). Those who have been exposed to these systems are more familiar with the different viewing and psychomotor effects that can result from temporal distortions which would otherwise not be present in the everyday, real-world human-machine experience. Many of today’s computing and simulation environments are capable of rendering

graphics at 30 Hz and higher. Operators of these advanced systems may therefore be unaccustomed to the effects of low FR and lag. For instance, Liu et al. (1993) suggest a minimum update rate of 2 Hz for experienced users and 10 Hz for inexperienced users of a teleoperation tracking task. Adaptation to poor temporal fidelity has also been demonstrated. Increasing the operators' exposure to low temporal fidelity can aid performance, and training is one way to accomplish adaptation (see Johnson & Caird, 1996).

2. Psychomotor Performance

2.1 Placement Performance

According to Fitts' Law, the time required to acquire a target is a function of (a) the physical distance to the target and (b) the physical size of the target (Fitts, 1954). The interaction between low FR on Fitts' Law was assessed by Bryson (1993, Experiment 2). This placement task involved moving a cursor from an initial position to a final position in a computer system. The performance means showed that increased lag and low FR have similarly detrimental effects on placement performance. More specifically, lags and FRs greater than 250 ms (< 4 Hz) dramatically increased the difficulty level of the task. Furthermore, the effect of great lag and low FR was less pronounced in the participant who was experienced with VEs with poor SR. In addition, Massimino and Sheridan (1994) suggested that frame rate as low as 5 Hz might be viable for placement tasks if force feedback were available.

In Liu et al. (1993), operators performed pick-and-place tasks while wearing HMDs. They found that operators who were experienced with HMDs were able to perform the placement tasks at update rates as low as 10 Hz but had significantly more errors below 2 Hz. Those who were inexperienced demonstrated impairments once the update rate dropped below 30 Hz, which suggests that experience level can moderate the relationship between FR and performance. Liu et al. also observed that task completion time was longer at update rates below 10 Hz.

Meehan, Insko, Whitton, and Brooks (2002) assessed placement performance in VEs; however, they also measured the physiological reactions imposed by various FRs. Lower FRs can impair performance and feelings of presence. For instance, the 10-Hz condition caused many participants to lose a sense of balance, causing anomalous dependent measure scores which consequently required readjustment. The change in heart rate was significantly higher in the 10-Hz than in the 15-Hz condition, indicating increased stress at the lower FR. Reported behavioral presence significantly increased as FR increased from 15 to 20 Hz and from 20 to 30 Hz.

Watson et al. (1997) examined placement performance in the context of variable FRs, using the sinusoidal method to calculate standard deviations in frame time. Average placement and grab times significantly improved when mean FR increased from 10 Hz to 20 Hz. In a later study, Watson et al. (1998) again assessed the effects of FR means and standard deviations on grasping

and placement tasks. This time, standard deviations were calculated with the frame-latency manipulation method and were absolute values of FRs (e.g., 4 Hz). Grasp time and the number of grasp attempts were significantly greater at the 9-Hz mean FR and when the standard deviation of system responsiveness (SDSR) was 4 Hz. Overall, grasping performance was impaired the most when mean FRs were low and SDs were high. Based on these results, Watson et al. (1998) speculated that improving the mean FR above 17 Hz may not necessarily increase grasping performance; to test this, a second study was conducted with a set of higher FRs. FR SDs were based on percentages of FRs (e.g., 5.6% of 17 Hz). It was found that increasing FR from 17 to 25 Hz did not significantly improve grasping performance, as hypothesized. Improved placement performance occurred at higher mean FRs and lower standard deviations, as was also found in Experiment 1. Overall, these results suggest that there may be a grasping performance threshold at higher FRs (such as at 17 Hz) and that grasping performance may be compromised only at lower mean FRs (such as 9 and 13 Hz).

Methods of calculating SDs in frame time have also been compared. In a third experiment, Watson et al. (1998) tested the hypothesis that SDSR control via absolute values was inferior to SDSR control via percentages of mean FR. The SDs were manipulated as absolute values of FRs (e.g., 4 Hz). Results showed that there was a significant increase in grasp time only when the FR was at the lowest (17 Hz) and SDSR was highest (7.56 Hz). A reduction in the SR range occurred at higher FRs, and therefore absolute FR control did not yield many significant effects. Thus, Watson et al. suspected that SR control based on absolute FR values may be inferior to SR control based on percentages of mean FRs.

2.1.1 Placement Task Conclusion

Results from studies that have manipulated a constant FR indicate that 10 Hz and less can be detrimental to placement performance in a VE; higher FRs are needed for participant performance and comfort. Specifically, the research has indicated that FRs less than 4 Hz seem to dramatically increase the difficulty level of the task (Bryson, 1993). Also, participants in VEs experience discomfort, balance loss, and increased heart rate at 10 Hz (Meehan et al., 2002). However, the variable FR approach may be more accurate when FRs are low, since standard deviations and fluctuations of FRs are important considerations (Watson et al., 1997). FR thresholds for ideal performance in variable FR configurations are probably similar to constant FR thresholds. Watson et al. (1997) found that grasping performance was compromised only at lower mean FRs such as the 9 and 13 Hz. For improved placement performance, the average FR should increase to at least 17.5 Hz (Watson et al., 1998) or 20 Hz (Watson et al., 1997).

2.2 Tracking Performance

Bryson (1993, Experiment 1) assessed tracking performance at various FRs and found that in general, normalized error was linearly dependent on frame time. Furthermore, the slope of this linear relationship depended on the frequency of the targets moving in a sinusoidal path. Thus, longer frame times (i.e., lower FRs) at higher frequencies of target motion produced the greatest

tracking error. In consideration of these results and those from Experiment 1 (see placement performance section), Bryson (1993, Experiment 1) concluded that frame time effects are congruent with those of delay in tracking tasks. Cai (2004) found that human figure recognition and tracking in a video were found to be a logarithmic function of FR, and a major improvement in this performance occurs by increasing FR from 0.05 Hz to 1 Hz. Thus, the minimal satisfactory FR was 1 Hz in normal viewing conditions. Performance increases somewhat between 1 and 7 Hz and then seems to stabilize from 7 Hz until the maximum tested value of 17 Hz.

Ware and Balakrishnan (1994) assessed the effects of low FR as well as lag in a target acquisition in VR display. Reaction time reductions were the most dramatic until 5 Hz but stabilized at around 10 Hz, beyond which, performance improvements are minimal. Thus, it may not be worth the extra cost to increase FRs beyond 10 Hz for this type of task and setting.

Vehicle control is considered to be a tracking task since the driver must maintain position of the vehicle within the lanes following a specific pathway (Watson et al., 2003). In a study of teleoperation of unmanned ground vehicles (UGVs), McGovern (1991) did not find driving performance degradation when image update rates were lowered from 30 to 7.5 Hz. On the other hand, Van Erp and Padmos (2003) reported that, when update rate dropped below 5 Hz in an indirect driving task, participants' lateral control significantly degraded. Day (1999) also assessed the effects of low FRs on a remote vehicle driving task. Mean task completion times and mean time in error increased as FR decreased, and performance for FRs 1 through 4 Hz was significantly lower than for the control condition, 25 Hz. Not surprisingly, post-task questionnaires indicated that 50% of participants felt they would have performed tasks significantly better with higher quality video.

Teleoperation-based tracking performance is of particular importance in FR studies, as communication problems can arise from bandwidth limitation (Liu et al., 1993). The UGV operator faces possible sources of signal degradation in the forms of physical distance from the UGV, obstacles, and electronic jamming (French et al., 2003). Successful teleoperation therefore relies on tracking performance in terms of navigation as well as target tracking. Liu et al. found that, similar to their placement task performance previously discussed, operators who were experienced with HMDs were able to perform tracking tasks at update rates as low as 10 Hz but had significantly more errors below 2 Hz. Inexperienced operators, on the other hand, showed a performance degradation almost immediately when FRs started to decrease. French et al. found that low FRs (i.e., 2 and 4 Hz) yielded significantly longer navigation times and higher cognitive, visual, and subjective workload ratings, but not target identification or situational awareness. French et al. concluded that 16 Hz is ideal for UGV teleoperation. However, to obtain effective task performance, a minimum of 8 Hz is necessary.

Display format and viewing characteristics can also interact with FR to impact manual tracking performance. Lion (1993) considered the differential effects for stereoscopic and monoscopic displays, as well as the use of head-coupled imagery.

The 33-Hz FR yielded better manual tracking performance than the 22-Hz FR. The cursor was also kept closer to the target 21% more of the time in the 33-Hz condition as opposed to the 22-Hz condition. There was also a significant interaction between stereo displays and FR, with better performance in the stereo 33-Hz condition.

An interaction between viewing condition and FR was found by Richard et al. (1996). Tracking time was fastest and stable in the range of 14 Hz to 28 Hz in the mono condition but remained stable at FRs as low as 7 Hz in the stereo condition. Stereo vision also continued to improve performance much more than that of mono vision when the FR dropped below 7 Hz. After 10 trials at 1 to 7 Hz in the mono condition, the mean target capture time produced a flat curve, suggesting cessation of learning. However, in the stereo condition, the mean capture time was lower overall, and the curve appeared mostly flat from the earliest trials. Thus, less learning took place at 1 to 7 Hz in the stereo condition.

Lampton, Knerr, Goldberg, Bliss, Moshell, and Blau (1994) observed that FR degradations affect participants' tracking performance in a VE. Although the FRs were not systematically manipulated, Lampton et al. did find that the slow FRs (i.e., approximately 5 Hz) made the 3-D tracking tasks very difficult. It was reported that participants were able to keep the cursor on the moving target less than 9% of the time.

Ellis et al. (1999) examined tracking performance in VEs at various FRs and degrees of latency. Decreased FR (e.g., 6 Hz versus 20 Hz) significantly increased root mean square (rms) error, increased perceived control, and decreased feelings of stability. Participants' judged realism was not affected by the various FR and latency values, however.

Arthur et al. (1993) manipulated the effects of stereo versus mono displays as well as the use of head-coupled imagery. Error rates in a 3-D tree-tracing task were measured. Response time increased along with increased lag and the lower FR of 10 Hz. Regression equations indicated that lag likely contributed more to performance effects than did reduction in FR.

2.2.1 Tracking Task Conclusion

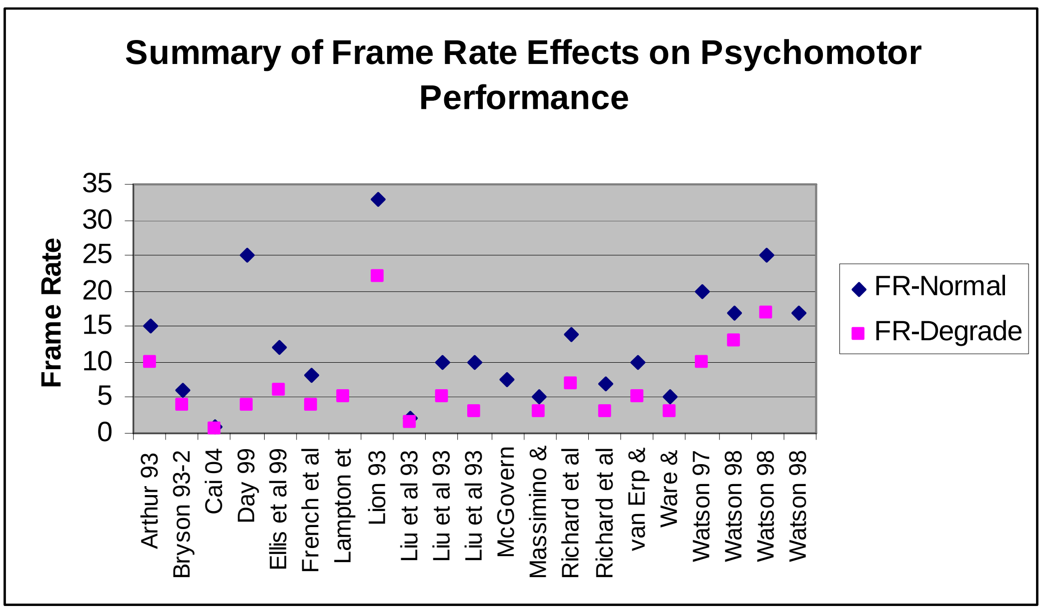
Overall, higher FRs such as 20 Hz and 33 Hz yielded better manual tracking performance than lower FRs such as 6 Hz and below (see Ellis et al., 1999; Lion, 1993). The detrimental effect of low FR is especially notable when the target moved at higher frequencies (Bryson, 1993, Experiment 1).

Teleoperation may require higher FRs. French et al. (2003) suggested that 16 Hz is ideal for tracking in UGV teleoperation, and that 8 Hz is an absolute minimum requirement. Additionally, Day (1999) demonstrated that remote vehicle control was significantly better at 25 Hz than at 4 Hz.

Acceptable tracking performance was found to be possible at very low FRs. Rates above 10 Hz may not be necessary for some applications; thus, systems with smaller bandwidth capability may still be effective. The minimal satisfactory FR was 1 Hz for tracking a moving human figure (Cai, 2004) and 2 Hz to 10 Hz for teleoperation for experienced operators (Liu et al., 1993). Finally, target acquisition in a 3-D environment seems to benefit most when FRs are increased to 10 Hz (Ware & Balakrishnan, 1994).

There may also be a significant interaction between stereo and FR, with better performance in stereo at higher FRs. It seems, therefore, that the combination of high FRs and stereo displays more closely mimics the real-world visual experience, thereby requiring less user adaptation and learning (Richard et al., 1996). This suggests that overall, if lower refresh rates are used, stereoscopic displays may compensate to boost operator performance. Based on these results, Lion (1993) proposes the importance of giving design priority to the development of systems with stereoscopic displays and higher FR.

A summary of these research findings is presented graphically in figure 1 and is also provided in more detail in appendix A.



(Note: Pink squares signify the FR level where human performance starts to significantly degrade. Blue diamonds signify the lowest FR levels where participants perform normally.)

Figure 1. Summary of FR effects on psychomotor performance.

3. Perceptual Performance

3.1 Target Recognition Performance

Some researchers examined the effects of slow FR on target recognition performance in the military context. For example, French et al. (2003) investigated robotic operators' target identification performance using a UGV. Their simulated degradation of video feed from the UGV included 2, 4, 8, and 16 Hz. They found that FRs as slow as 2 Hz did not significantly affect their performance, including target identification and situational awareness.

Chen, Durlach, Sloan, and Bowens (2005) conducted a robotic control study in a simulated military environment. They manipulated the FRs (5 versus 30 Hz) of the sensor video feed of the simulated unmanned aerial vehicle and UGV. Participants' tasks included target detection and acquisition. Neither performance was significantly degraded as FRs dropped from 30 to 5 Hz.

Perception of the visual cues associated with speech and lip reading may also be considered a form of target recognition. Visual information can aid interpersonal communication for those with impaired hearing by means that coupled the visual cues of speech reading or "lip reading" with the limited auditory perception that remains. Sign language interpretation is a pattern recognition task which may depend on temporal resolution. FR is thought to impact specific aspects of lip reading, including the apparent duration of visual speech components such as mouth movements (Massaro, Beskow, Cohen, Fry, & Rodriguez, 1999) and dynamic components such as syllable timing (Summerfield, 1979).

3.1.1 Constant FR Effects of Target Recognition

Johnson and Caird (1996) found that low FR can impair recognition of American Sign Language gestures. Although there was no significant main effect for FR, means indicated a trend for impaired performance and increased error rate at lower FRs (e.g., 1 and 5 Hz). However, over the course of additional trials, there was an improvement in performance. Training may therefore be useful when bandwidth is limited.

Adding audio cues to visual presentation can aid target recognition. Frowein et al. (1991) assessed speech reception target recognition in the domain of video telephony. Audio-visual recordings of common sentences were presented in both audio-visual and audio-only modes. Participants were asked to repeat each sentence immediately after the presentation. At 5 to 6 Hz, performance in the audiovisual condition was significantly better than the audio condition, and at 15 Hz, the added performance improvement stabilized, with no further performance benefits for the 30-Hz condition. Thus, there may be an interaction between presentation mode and FR in speech perception.

Vitkovitch and Barber (1994) hypothesized that the perception of the speaker's facial movement was important to help listeners to perceive speech. In this study, participants listened to two simultaneous recordings of a message and shadowed (i.e., repeated) the words of the target message. Recordings were in either audio-only or audio-visual format. Having a visual display did improve performance over an audio-only display. Even audio-visual video presented at the lowest FR (8.3 Hz) yielded improved performance over the audio-only condition; this is consistent with Frowein et al. (1991). Across all FRs, performance improved when FR was increased. However, there was no significant performance benefit from increasing the FR from 16.7 Hz to 25 Hz, which suggests that 16.7 Hz may be adequate for video transmission for recognition tasks of this nature; this is also consistent with Frowein et al.

In another study by Vitkovitch and Barber (1996, Experiment 1) participants lip read number sequences in the range of 1 through 30 in a visual-only condition. By turning off the sound, Vitkovitch and Barber (1996) were able to determine that the detrimental effect of low FR is not attributable to audiovisual asynchrony. GL of the image was also manipulated. Performance accuracy significantly improved when FRs were increased from 8.3 Hz to 25 and from 8.3 Hz to 16.7. There was no significant gray scale and FR interaction, which suggests that both may be independent (yet additive) sources of visual cues in lip reading ability. In a second experiment, Vitkovitch and Barber (1996) sought to assess whether repeated exposures to stimuli of low FR and limited gray scales can aid participants' lip reading ability. Both digital and analog formats as well as GL were compared. There was no improvement in accuracy over time for those in the low FR (8.3 Hz). This may indicate that the high perceptual demand of the low FR was too great, and thus increased experience was not enough to allow participants to compensate for the visual degradation. Main effects of both FR and GLs indicate that performance was higher at 25 Hz than 8.3 Hz as well as 16 GL compared to 8 GL. Results of both experiments show that FRs higher than 8.3 Hz are necessary for lip reading with 16.7 Hz being adequate.

Williams, Rutledge, Garstecki, and Katsaggelos (1997) investigated the effects of FR and the recognition of visemes or visual phonemes (Fisher, 1968), which are the visual speech cues such as mouth movements and teeth positions that accompany speech sounds. Generally, viseme recognition decreased along with decreasing FR. Often, viseme recognition dramatically dropped when the FR was reduced from 5 Hz to 2 Hz.

The visual distortion caused by low FR can result in an asynchrony with the audio components of the presentation. Knoche et al. (2005) manipulated both FR and audiovisual skew upon the ability of participants to identify the middle consonants of nonsense words. Results showed that lower FRs worsen the effects of negative audio skew (in which audio leads visual). Conversely, positive skews (in which visual leads audio) can improve consonant comprehension. At FRs between 10 and 15 Hz, audio lags between +127 ms and +167 ms can improve comprehension beyond that which normally occurs at 30 Hz. This may be because longer frame times allowed participants to "close the gap" between audio and visual stimuli. Additionally, the authors suspect there is a ±120-ms limit on the ability for humans to integrate audiovisual information

(any more or less suggests great asynchrony and possible failed integration). Whereas audio and video can be perceived in synchronization with each other anywhere between ±120 ms and 30 Hz, this window changes to -54 ms to +186 ms at 10 Hz. The implications of these results are that in a "noisy" environment, video at 10 Hz will be effective if audio lags visual by +120 ms to +170 ms.

FR studies can also apply to dynamic medical displays, such as x-ray fluoroscopy, cardiac cineangiography, real-time two-dimensional (2-D) ultrasound, rapid sequence nuclear magnetic resonance imaging (MRI), radioisotope ventriculography, and ultrafast computer tomography. There is also a degree of "noise" and contrast involved in these displays, which can further complicate the detection of low contrast signals. Whiting et al. (1991) examined the effects of FR on signal detection in a radiological application. Higher FRs aided signal detection performance, specifically as the FR progressed from 0 Hz (static image) to approximately 4 Hz. It then improved modestly until the FR increased to 16 Hz, then mildly improved at higher FRs thereafter. Although 100 to 200 msec was previously suggested as the maximum persistence of visual memory, the results of current study suggest a 1500-msec decay time in this task.

3.1.2 Variable FR Effects of Target Recognition

Variable FR configurations have been tested in target recognition. Parkhurst and Niebur (2001) employed the velocity-based LOD graphics rendering technique to present target objects in a virtual room. FRs were held constant at 6 Hz or were variable so that they were allowed to increase with decreasing LOD as the observer turned his or her head to search for targets. Target detection accuracy did not change because of LOD changes. Reaction times increased with decreasing LOD in the constant FR condition, but in the variable FR condition, reaction times decreased when LOD decreased, likely because the extra bandwidth was allocated toward generating a higher FR. Overall, there was support for the velocity-based LOD rendering technique, since faster rendering times associated with decreased LOD can aid visual search performance.

3.1.3 Target Recognition Performance Conclusion

Some researchers examined the effects of slow FR on target recognition performance in the military context. For example, French et al. (2003) investigated robotic operators' target identification performance and found that FRs as slow as 2 Hz did not significantly affect their performance (as compared to when FRs were 4, 8, and 16 Hz). Similarly Chen et al. (2005) did not observe significant target detection performance degradation as FRs dropped from 30 to 5 Hz.

Speech reading is one form of target recognition. Frowein et al. (1991) concluded that FR is an important contributor to speech reading perception and that FRs until 15 Hz can improve this performance. Comparably, Vitkovitch and Barber (1994, 1996) concluded that 16.7 Hz may be

adequate, and lower rates, such as 8.3 Hz to 12.5 Hz, may result in a great loss of dynamic visual information and audio-visual mismatch, thereby causing major performance decrements. Conversely, Williams et al. (1997) considered the low rate of 5 Hz to be the minimum threshold for continuous speech reading. Another important aspect of speech reading is the potential for audio accompaniment, which can be skewed at lower visual FRs. For instance, at 10 Hz, the audio presentation should lag the visual presentation by at least +40 ms (Knoche et al., 2005).

Observers may be able to adapt to low FRs, however. If there is enough opportunity to learn sign language gestures, low multimedia rates of 1 and 5 Hz may be adequate (Johnson & Caird, 1996).

Continuous FR presentation in a purely visual signal detection task demonstrated an apparent 16-Hz threshold for adequate performance. Increasing FR beyond this level improved performance only mildly (Whiting et al., 1991).

Another approach to the target detection environment is the use of a variable FR system. The velocity-based LOD rendering technique is one such approach to determining FR. It can yield faster graphics rendering times when high LOD is not necessary, and this in turn can improve visual search performance (Parkhurst & Niebur, 2001).

3.2 Perception and Psychophsics

The effects of slow FRs on human perception have been examined in a wide variety of environments. For example, in a study conducted in a VE, Piantanida, Boman, and Gille (as cited in Reddy, 1997) found that participants' depth and egomotion perception degraded when FRs dropped. On the other hand, Van Erp and Padmos (2003) assessed the effects of slow update rates on the viewing system for indirect driving and observed that an update rate as low as 3 Hz did not appear to affect participants' speed perception.

Augmented reality (AR), in which computer graphics are overlaid onto the physical environment through transparent HMDs, has also been used to study the effects of slow FRs. Effective AR depends, in part, on the mechanisms of human visual perception, such as depth cues and motion detection. Lai and Duh (2004) assessed the role of different FRs on the perception of visualization dynamic information via the change in bar graphs. (The bar graphs were presented in an HMD.) Users can visualize changes in dynamic information displays by tracking the motion of the stimulus (e.g., vertical changes bar graph height). Users can also anticipate the future motion of the stimulus change as a function of the implied velocity of the stimulus (i.e., representational momentum; see Freyd & Finke, 1985). Thus, the display's ability to convey motion can impact the perception of dynamic information representation. Participants judged the percentage change in a dynamic 3-D bar chart (e.g., the rate at which the height of a bar graph was increasing). Interestingly, the greatest judgment inaccuracies were made at the fastest FR, 160 Hz. It was found that participants overestimated the percentage at lower speeds and underestimated at higher speeds. This may be because in the slower speeds, participants use

cognitive resistance (see Finke & Shyi, 1988) in later stages of the presentation to reduce the degree of representational momentum. It is also important to consider the typical human cognitive processing speed of 170 msec (Card et al., 1983) since changes that occur below this threshold may not be accurately perceived. This may explain the performance improvements for the longer frame times (i.e., slower FRs).

Mastoropoulou and Chalmers (2004) hypothesized that music could be used as a distractor to affect the user's perception of time enough to de-emphasize slower rendering times. Participants with computer graphics experience were tested. Animated clips were compared at different FRs, and each compared pair had a difference of 4 Hz (16 versus 20 Hz or 12 versus 16 Hz). The two types of music that accompanied the animations were "slow tempo and relaxing" and "fast tempo and exciting". Frequency analyses showed that slow tempo music decreased the perceived scene velocity. Contrary to the hypothesis, playing fast tempo music did not convince observers that the clip was shorter and progressed at a higher temporal rate. The lack of support for the hypothesis could be because a difference of 4 Hz was not enough for participants to perceive a velocity difference when the two different FRs were compared.

Pfautz (2002, Experiment E) was interested in the impact of spatio-temporal sampling on the perception of constant velocity motion. There was an interaction between FR and stimulus velocity, so that higher velocities at higher FRs (e.g., 15 and 60 Hz versus 5 and 7.5 Hz) yielded more accurate response distances. In a second related experiment, Pfautz (2002, Experiment F) assessed the effects of viewpoint manipulation in an air traffic control collision task. The task involved making a time-to-contact judgment for two moving aircraft on a screen. The higher FR, 20 Hz, provided greater judgment accuracy than 7.5 Hz. Allowing participants to alter their viewpoint impaired this accuracy, however.

Reddy (1997, Experiment 1) assessed performance in a virtual heading task while manipulating FR at either 2.3 Hz (considered to be excessively low) or 11.5 Hz (considered to be moderately acceptable). In the heading task, the subject was passively navigated through the VE with his or her direction of fixation oriented differently from the direction of movement, and the task was to determine whether he or she was moving toward the left or right of the fixation point. The higher FR of 11.5 Hz had clear performance benefits in terms of accuracy and task completion time. The same task was again executed in a second experiment (see Reddy, 1997, Experiment 2). Higher FRs were manipulated in this experiment, this time with 6.7 Hz and 14.2 Hz. As in the first experiment, similar trends were found, so that accuracy and reaction time were better in the higher FR condition. More precise angle discriminations were possible at this higher FR.

3.2.1 Perception and Psychophsics Conclusion

Van Erp and Padmos (2003) assessed the effects of slow update rates of the viewing system for indirect driving and observed that an update rate as low as 3 Hz did not appear to affect participants' speed perception. Piantanida, Boman, and Gille (as cited in Reddy, 1997), on the

other hand, found that participants' depth and egomotion perception degraded when FRs dropped.

The perception of constant velocity motion seems to be best served by higher FRs such as 15, 20, and 60 Hz (Pfautz, 2002, Experiments E and F). However, there is an upper limit to the ideal FR. Excessively rapid FRs (e.g., 160 Hz) can impair the apparent rate of change in dynamic informational displays (Lai & Duh, 2004). On the other hand, differences of 4 Hz at modest FRs (e.g., in the range of 12 to 20 Hz) may be undetected by viewers, even if they are experienced with computer graphics (Mastoropoulou & Chalmers, 2004).

In heading performance, there is a strong performance benefit when the FR increases to 10 to 15 Hz; however, performance improvements taper off afterwards at higher rates. Thus, it seems that 15 Hz might be considered the minimum threshold for VEs. FRs below 10 Hz will yield sharp performance degradations, in terms of both response time and heading accuracy. Heading tasks have many parallels to other VE applications, such as driving and flight simulators, and so the results can extend to these domains, as well (Reddy, 1997).

A summary of these research findings is presented graphically in figure 2 and is also provided in more detail in appendix B.

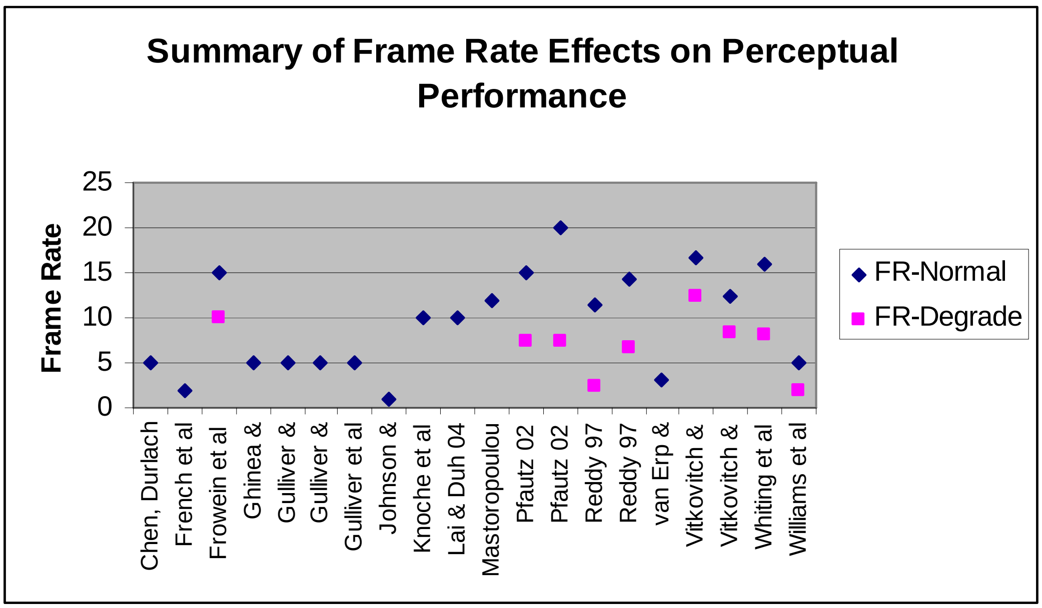


Figure 2. Summary of FR effects on perceptual performance.

4. Behavioral Effects

Eye movements are considered important in our understanding of visual perception, attention, and cognitive processes. The eye will focus on particularly informative areas of a display (Peiz, Canosa, & Babcock, 2000); thus, poor visual quality may fail to attract eye fixation. Quality of Service (QoS) refers to the goodness or degree to which the multimedia presentation is considered tolerable in terms of viewing experience and is partially determined by FR, which, in turn, is attributable to bandwidth limitation implications.

Gulliver and Ghinea (2004a) investigated changes in eye movements as influenced by low FRs. It was hypothesized that jerkier and disjointed video presentations from the low FRs would be more perceptually intolerable and annoying, thereby causing more variability in eye paths. Interestingly, no correlation was found between FR and eye path movements. Thus, Gulliver and Ghinea (2004a) suggest that lower FRs (e.g., 5 Hz) do not influence the flow of informational assimilation.

Individuals are able to conduct video-mediated conversations with the use of hand motions at FRs as low as 1 Hz (Chen, 2002) and one frame change every 5 seconds, although subjective measures indicated that participants thought this extremely low FR was ineffective (Chen, 2003). Thus, despite noticeably low temporal quality, these types of visual cues can retain their effectiveness.

Extremely slow FRs and their associated visual lag may cause cue conflict (i.e., discrepancy between visual and vestibular systems), which has been shown to induce cyber/simulator sickness (Kolasinski, 1995; Stanney, Mourant, & Kennedy, 1998).

5. Subjective Assessment

Varying FRs may influence the subjective ratings of video quality and viewing enjoyment. This may be of importance to service providers who need to know the minimum level of quality that their customers find acceptable, as well as viewers who need to be able to recognize the subject matter and observe smoother movements (McCarthy, Sasse, & Miras, 2004).

QoS involves spatial (intraframe) characteristics (e.g., picture resolution, color depth), temporal (interframe) characteristics (e.g., FR), as well as a spatiotemporal integration (e.g., as auditory effects that are in synchrony with the visual cues) (Apteker, Fisher, Kisimov, & Neishlos, 1995). It is related to the image quality or FR trade-off in bandwidth allocation, in which FR can be reduced in order to improve the spatial aspects of the video.

“Watchability” is a characteristic of video which includes the viewer’s acceptance of the video’s audio signals, the continuity of visual messages, lip movement-speech synchronization, and the relationship between the audio and visual message components (Apteker et al., 1995). Lowering FRs has been shown to reduce the watchability of video clips, so that 15 Hz might be just acceptable, 10 Hz is much less acceptable, and 5 Hz is very unacceptable (Apteker et al.). High action videos (e.g., sports clips) on a desktop display with a resolution of 352 x 288 pixels have yielded similar satisfaction ratings across the FRs of 25, 15, and 5 Hz (Ghinea & Thomas, 1998) and have been considered acceptable 80% of the time when FRs were only 6 Hz (McCarthy et al., 2004). When videos were viewed on a palmtop display (sized 176 x 144), low FR was found to be less acceptable than on a desktop display, so that the critical lowest acceptable FR value was 12 Hz, and 6 Hz was considered acceptable only 50% of the time.

Gulliver and Ghinea (2004b, 2004c, 2004d) found that degradation of perceived video quality and satisfaction was not noticeable when FR was reduced from 25 Hz to 15 Hz, but it was noticeable when the FR was reduced to 5 Hz. Thus, presentations made at 15 Hz and 25 Hz appear perceptually similar to the participants. An FR reduction from 30 to 1 frame changes every 5 seconds had minimal effect on engagement and enjoyment in a video-mediated conversation (Chen, 2003). Other studies have found that reductions in FR (i.e., from 25 to 15, and then to 5 Hz) often do not impair viewing enjoyment; however, there is a reduction in perceived quality (Gulliver, Serif, & Ghinea, 2004).

The relationship between FR and perceived quality may, however, be context dependent. Masry and Hemami (2001) found that perceived quality was higher for lower FRs (such as 10 and 15 Hz) in higher action sequences, but it was found unacceptable in clips involving less motion; this indicates a possible preference specific to motion types. In a similar vein, video clip subject matter may result in different levels of perceptual quality and user satisfaction, independent of FR (Gulliver & Ghinea (2004b). For example, across all FRs (5, 15, and 25 Hz), popular music videos had higher subjective quality and satisfaction ratings than a chorus video.

Quality of perception (QoP) is the perceptual experience of the user, including the enjoyment of watching the video, as well as the ability to analyze, synthesize, and assimilate information presented (see Ghinea & Thomas, 1998; Ghinea & Chen, 2003; Gulliver & Ghinea, 2004a, 2004b, 2004c, 2004d). Thus, QoP involves the viewer’s information processing. Multimedia can often be greatly degraded before perception, information assimilation, and learning are impaired. Ghinea and Thomas (2000) demonstrated that viewers could integrate visual details to learn and then correctly answer questions about the content of videos, even as FR was reduced from 25 to 5 Hz. Often, lower FRs (5 Hz) resulted in more correct answers about what had been viewed, possibly because there was more time to view frames before they changed (at 25 Hz, each frame is visible for 40 ms, but at 5 Hz, a frame is visible for 200 ms). The robustness of information assimilation despite low FR has been documented in other studies (see Ghinea & Thomas, 1998; Gulliver & Ghinea, 2000; Ghinea & Chen, 2003; Gulliver & Ghinea, 2004a, 2004b, 2004c, 2004d; Gulliver, Serif et al., 2004).

According to Ghinea and Chen (2003), cognitive style, such as field dependence (i.e., degree to which a person's perception of information is influenced by the contextual field) and field independence, were not moderators in the relationship between FR and QoP. Furthermore, eye path movement, which is associated with attentional and cognitive processes, did not differ across FRs of 5, 15, or 25 Hz (Gulliver & Ghinea, 2000d).

Van Breda, Jansen, and Veltman (2005) reported that UAV operators assessed their effort in viewing the simulated sensor feed as higher when the frame rate for the camera image was low (i.e., 3 Hz) compared to normal frame rates. Wilson and Sasse (2000) have shown that low FRs can cause viewers physiological strain, despite the fact that most of them did not report noticing a difference between videos presented at 5 and 25 Hz. Exposure to the 5-Hz condition resulted in greater experiences of stress, characterized by increased galvanic skin response, increased heart rate, and decreased blood volume pulse. The results of this study suggest that it may not be sufficient to measure subject reactions alone, since physiological effects can also occur. This partially corroborates the findings of Meehan et al. (2002), in which 10 Hz caused large increases in heart rate compared to higher FRs.

A summary of these research findings is presented graphically in figure 3 and is also provided in more detail in appendix C. Figures 1 through 3 are summarized graphically in figure 4.

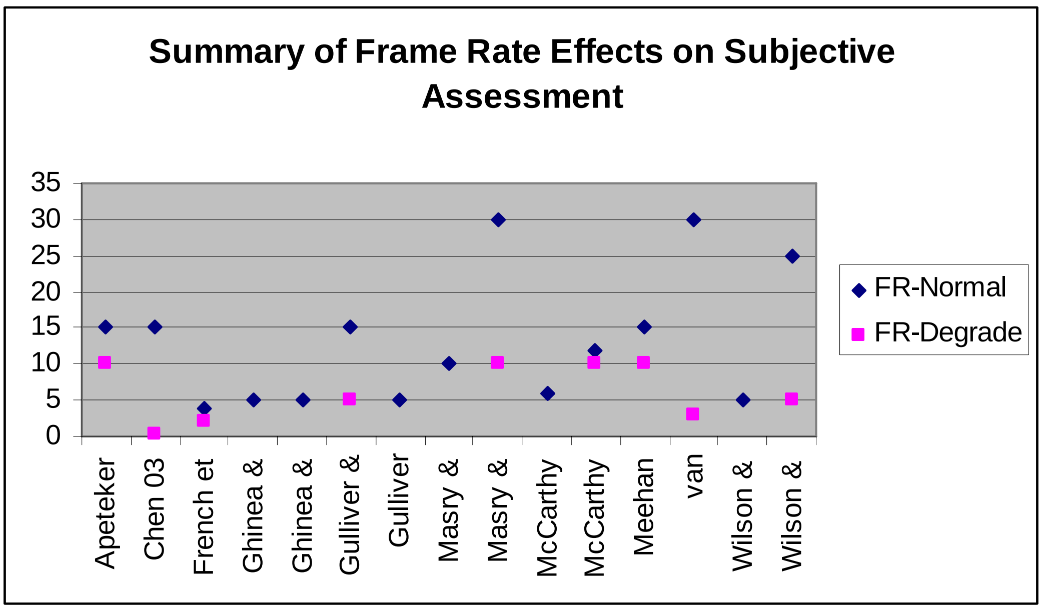


Figure 3. Summary of FR effects on subjective assessment.

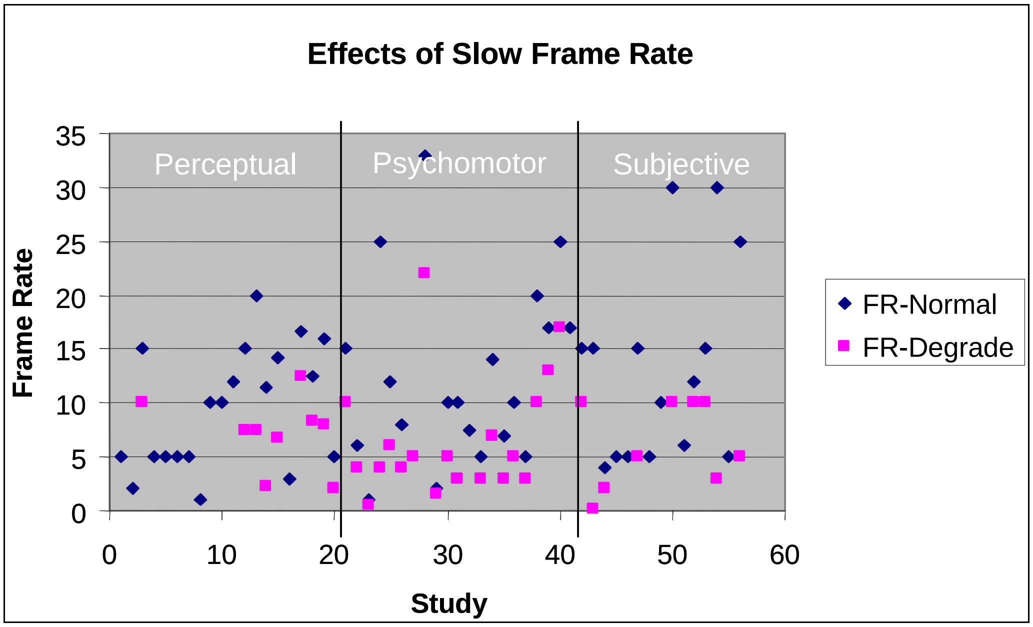


Figure 4. Summary of effects of slow FR (figures 1 through 3). (Note: The x-axis denotes the number that the study was designated. The list of studies with their corresponding numbers is provided in appendices A through C. Pink squares signify the FR level where human performance starts to significantly degrade. Blue diamonds signify the lowest FR levels where participants perform normally.)

6. Conclusions

Robotic systems of various sizes and capabilities will play an integral role in the U.S. Army's FCS program (Barnes, Cosenzo, Mitchell, & Chen, 2005). According to Mait and Grossman (2002),

> …although the operational concept for FCS requires UGVs to sense the battlefield and react on their own with minimal human interaction, current technology can best be described as remote controlled or teleoperated. Semiautonomous operation, suitable for sensing and indirect fire functions, will not be available until 2010, and fully autonomous systems (necessary for direct fire, battle damage assessment, and reconnaissance, surveillance, targeting, and acquisitions) will not be available until 2015 or later. (http://www.ndu.edu/inss/DefHor/DH13/DH13.htm)

Effectiveness of employing these robotic assets, especially if teleoperation will be involved, will in large part be determined by the quality of the video feeds of the remote environment, which will be the main source of information for the robotic operator to perform his or her tasks (e.g., target detection, tele-manipulation). Since bandwidth constraints may be an issue in the future battlefield (Mait & Grossman, 2002) and high FR streaming video may not be available at all

times, it is important to examine human performance issues that may be associated with low FRs.

In this report, we reviewed more than 50 studies and summarized them in the areas of psychomotor performance, perceptual performance, behavioral effects, and subjective perception. Generally, psychomotor performance improves at higher FRs and lower standard deviations of FR. In placement tasks, 4 Hz may be too low for VE performance, and 10 Hz may disrupt human balance. Experimental results have suggested a minimum threshold of 17.5 Hz for successful placement performance (Watson et al., 1997). Tracing performance may also require more than 10 Hz.

For teleoperation, higher FRs such as 16 Hz are suggested to aid in navigation and target tracking. A rate of approximately 10 Hz may suffice for HMD-facilitated tracking. This lower required FR will be useful for releasing bandwidth for other uses, such as rendering more graphically detailed images.

Speech reading is an often-studied form of target recognition. Generally, 13 Hz may be too low for speech reading from video transmission; rather, at least 15 Hz may be necessary. However, with appropriate learning opportunity, rates around 5 Hz (and possibly less) may be sufficient. As with video speech reading, target detection in a visual radiological task may be significantly more successful at 16 Hz. Perceptual VE task performance seems to be best served by FRs above 15 Hz. This includes perceiving motion of a constant velocity and heading performance.

Individuals seem to be able to gather content-based information about videos that are viewed at low FRs such as 5 Hz. While this FR is very low, it may benefit information assimilation because each frame remains on the screen for a relatively longer duration compared to frames that are presented at higher rates. This provides viewers with more time to observe each frame. Eye movement studies support these findings; the lack of effect for FR upon eye movements indicates that there are not significant changes in attentional and cognitive processes.

In terms of watchability and satisfaction, FRs of 5 Hz can appear “unacceptable” and of lower visual quality. Still, they are often considered to be enjoyable to watch despite the temporal distortion. However, FR reductions from 25 to 15 Hz are often perceptually similar in appearance to viewers.

Also, FRs at 10 Hz and below have been shown to cause stress in terms of physiological reactions in addition to general performance decrements.

Overall, there seems to be strong support for a threshold of around 15 Hz for many tasks, including those that are psychomotor and perceptual in nature. Only Lion (1993) and Watson et al. (1998, Experiment 2) (of the 56 studies reviewed) showed significant performance degradation associated with FRs higher than 15 Hz. Less impressive yet acceptable performance may be accomplished at around 10 Hz for many tasks. However, it is important to consider that individuals may be more susceptible to stress symptoms at FRs at and below 10 Hz. Information

assimilation seems to be far more impervious to the detrimental effects of FR, since participants can observe and retain much information from clips presented at rates as low as 5 Hz. Subjective reactions to quality and watchability of videos seem to support rates of 5 Hz, although videos presented at 15 Hz and above are generally more widely preferred.

These generalizations regarding superior and acceptable FRs may also be subject to the effects of several moderators. The majority of the studies reviewed have involved other independent variables and equipment characteristics that could be contributing to or detracting from the proposed effects of various FRs.

The use of variable FR manipulation has been recommended over constant FRs because of its proposed accuracy advantage (Watson et al., 1997). There are many different ways to determine the standard deviations in laboratories; however, some techniques may be more accurate in terms of how FR truly varies in real-world systems (e.g., standard deviations based on percentages of mean FRs).

Stereoscopic displays will likely enable a performance advantage over monoscopic displays, and when possible, they should be used to assist operators in compensating for lower FR presentations. If displays are stereoscopic, FRs as low as 7 Hz may be adequate, but monoscopic displays may only be useful for FRs as low as 14 Hz (Richard et al., 1996).

User experience may also be an important moderator. Individuals with HMD use experience were able to tolerate FRs as low as 10 Hz in tracking, whereas inexperienced participants needed 30 Hz (Liu et al., 1993). This difference in tolerable FR is quite large, and so it is clear that demographics should be measured and controlled when temporal distortion is manipulated.

7. References

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Appendix A. Summary of FR Effects on Psychomotor Performance

Study No.	Author(s) and Date	FR Manipulation	Task Type	Measures	Findings
1	Arthur et al. (1993)	**10**, **15**, 30 Hz	3-D tree-tracing	Accuracy Speed	Highest response time at lowest FR (10 Hz condition).
2	Bryson (1993, Experiment 1)	2, 3, **4**, **6**, 10, 20, 30, 60 Hz	Tracking	Accuracy	Longer frame times (i.e., lower FRs) at higher frequencies of target motion produced the greatest tracking error.
2	Bryson (1993, Experiment 2)	2, 3, **4**, **6**, 10, 20, 30, 60 Hz	Placement	Accuracy Speed	Performance worsened by increased lag and lower FR, especially frame times longer than 0.25 sec. Experienced participants less impaired by low FR.
3	Cai (2004)	Range from **0.5**, **1**, to 17 Hz	Tracking a moving human figure	Accuracy	Minimal satisfactory FR was 1 Hz for this type of task in normal viewing conditions.
4	Day (1999)	1, 2, 3, **4**, and **25** Hz	Tracking	Accuracy Speed	25 Hz is ideal; overall performance is worse for FRs of 1 to 4 Hz.
5	Ellis et al. (1999)	**6**, **12**, and 20 Hz	Tracking	Accuracy Perceived control & stability	Decreased FR significantly increased rms error, increased adapted Cooper-Harper scale scores, and decreased stability.
6	French et al. (2003)	2, **4**, **8**, and 16 Hz	Tracking	Accuracy Speed	16 Hz is ideal for UGV teleoperation. To get effective task performance, at least 8 Hz should be used.
7	Lampton et al. (1994)	**5** Hz	3-D Tracking	Accuracy	Participants could only keep the cursor on the moving target less than 9% of the time.
8	Lion (1993)	**22** and **33** Hz	Tracking	Accuracy	33 Hz FR yielded better performance than 22 Hz FR.
9	Liu et al. (1993)	0.1, 0.25, 0.5, 1, **1.5**, **2**, 3, 5, 10 & 30 Hz	Tracking-experienced participants	Accuracy Speed	Suggest a minimum update rate of 2 Hz for experienced VE users.
10	Liu et al. (1993)	0.1, 0.25, 0.5, 1, 1.5, 2, 3, **5**, **10** & 30 Hz	Tracking-inexperienced participants	Accuracy Speed	Suggest a minimum update rate of 10 Hz for inexperienced users.
11	Liu et al. (1993)	0.25, 1, 1.5, 2, **3**, **10** & 30 Hz	Placement	Accuracy Speed	Suggest a minimum update rate of 2 Hz for experienced VE users and 10 Hz for inexperienced users.
12	McGovern (1991)	**7.5**, 30 Hz	Tracking	Vehicle Control	Low FR did not significantly affect driving performance on a cone-marked route.
13	Massimino & Sheridan (1994)	**3**, **5**, 30 Hz	Placement	Accuracy Speed	Task completion time at 3 Hz was significantly slower than 5 and 30 Hz. While FR of 30 Hz is best, reduced FRs are viable, especially if force feedback is provided.
14	Richard et al. (1996)	1, 2, 3, **7**, **14**, 28 Hz	Tracking & Grasping - Mono condition	Accuracy Speed	Within the mono condition, completion time was fastest and stable from 28 Hz down to 14 Hz.
15	Richard et al. (1996)	1, 2, **3**, **7**, 14, 28 Hz	Tracking & Grasping - Stereo condition	Accuracy Speed	Within the stereo condition, it was fastest and remained stable from 28 Hz down to 7 Hz.
16	Van Erp & Padmos (2003)	3, **5**, **10**, 30 Hz	Tracking	Vehicle Lateral Control	Lateral control of vehicle movement was degraded when FR dropped below 5 Hz.
17	Ware & Balakrishnan (1994)	0.666, 1, 2, **3**, **5**, 10, 15, 60 Hz	Target acquisition in a 3-D environment	Speed	10 Hz is approximately the lowest threshold for adequate target acquisition performance.

18	Watson et al. (1997)	**10** and **20** Hz	Placement	Speed Accuracy	Performance significantly improves when average FR increases to 20 Hz. Average number of grab attempts and percentage of correct attempts were significantly lower at 20 Hz.
19	Watson et al. (1998, Experiment 1)	9, **13**, and **17** Hz	Placement Grasping	Speed Accuracy	Grasping performance may be compromised only at lower mean system responsiveness (MSR) FRs (such as 9 and 13 Hz MSRs. A 2Hz SDSR may be the lowest threshold at which grasp time performance is affected. Lower standard deviations (e.g., 0.5 Hz) may not impact grasping time.
20	Watson et al. (1998, Experiment 2)	**17**, **25**, and 33 Hz	Placement Grasping	Speed Accuracy	Better placement performance at higher MSRs and lower SDSRs. There may be a grasping performance threshold at 17 Hz.
21	Watson et al. (1998, Experiment 3)	mean FRs **17**, 33, and 41 Hz, each with SDs of 0.50, 3.78, and 7.56 Hz	Placement Grasping	Speed Accuracy	Increase in grasp time only when the FR was at the lowest (17 Hz) and SDSR was highest (7.56 Hz). Placement time was longer when FR was 17 Hz.

Appendix B. Summary of FR Effects on Perceptual Performance

Study No.	Author(s) and Date	FR Manipulation	Task Type	Measures	Findings
22	Chen et al. (2005)	**5** and 30 Hz	Target detection	Accuracy	No differences between the FRs.
23	French et al. (2003)	**2**, 4, 8, and 16 Hz	Target identification	Accuracy	No differences among the FRs.
24	Frowein et al. (1991)	5, 6, 7.5, **10**, **15**, and 30 Hz	Target recognition & Info processing	Verbal information recall	FRs up to 15 Hz can improve speech reading perception. FRs higher than 15 Hz do not further improve performance.
25	Ghinea & Thomas (2000)	**5**, 15, 25 Hz	Information processing	Information assimilation	Information assimilation can be successful at 5 Hz, and this low FR may provide the viewer with more time to learn the content of the frame.
26	Gulliver & Ghinea (2004a)	**5**, 15, and 25 Hz	Information processing	Eye path movement	No correlation was found between FR and eye path movements. In this setting, 5 Hz was equally effective as 25 Hz.
27	Gulliver & Ghinea (2004, b, c, & d)	**5**, 15, and 25 Hz	Information processing	Information assimilation Eye path movement	Low FR of 5 Hz has no effect on information assimilation. Eye path movement, which is associated with attentional and cognitive processes, did not differ across FRs of 5, 15, or 25 Hz.
28	Gulliver, Serif, & Ghinea, (2004)	**5**, 15, 25 Hz	Information processing	Information assimilation	Low FR of 5 Hz has no effect on information assimilation.
29	Johnson & Caird (1996)	**1**, 5, 15, or 30 Hz	Target recognition Information processing	Learning	1 and 5 Hz may be adequate for learning these types of gestures in multimedia, if there is enough learning opportunity.
30	Knoche et al. (2005)	**10**, 15, 30 Hz	Target recognition	Accuracy	In a “noisy” environment, video at 10 Hz will be effective if audio lags visual by +120 ms to +170 ms. If the audio lags by more than 170 ms, a full FR of 30 Hz should be reduced to 10 Hz.
31	Lai & Duh (2004)	**10**, 40, 80, 120, 160 Hz.	Judgment of visual percentage change	Accuracy	Greatest inaccuracies were made at the fastest FR, 160 Hz (excessively rapid). In AR, participants underestimated the percentage increase, except for in the 10-Hz condition.
32	Mastoropoulou & Chalmers (2004)	16 vs. 20 Hz or **12** vs. 16 Hz	Viewing animated clips	Temporal perception	A difference of 4 Hz was not enough for participants with computer experience to perceive a velocity difference between the two FRs (12 vs. 16 Hz and 16 vs. 20 Hz).
	Parkhurst & Niebur (2001)	Constant at 6 Hz, or varied (median FRs ranged from 9 to 31.5 Hz)	Target recognition	Accuracy Reaction time FRs and frame rendering times (computer performance)	Reaction times increased with decreasing LOD in the constant FR condition, but in the variable FR condition, reaction times decreased when LOD decreased.
33	Pfautz (2002, Experiment E)	5, **7.5**, **15**, 60 Hz	Time-to-contact judgment	Accuracy	No significant main effect for FR. Interaction between FR and velocity; higher velocities at higher FRs yielded more accurate response distances.
34	Pfautz (2002, Experiment F)	**7.5** Hz vs. **20** Hz	Time-to-contact judgment	Accuracy	20 Hz FR provided greater judgment accuracy.

35	Reddy (1997, Experiment 1)	**2.3** Hz and **11.5** Hz	Directional (orientation) judgment	Accuracy Reaction time in heading task	11.5 Hz had significantly better performance than 2.3 Hz condition.
36	Reddy (1997, Experiment 2)	**6.7** Hz and **14.2** Hz	Directional (orientation) judgment	Accuracy Reaction time in heading task	15 Hz might be considered the minimum for VEs, and higher FRs will continue to show better performance, but at a reduced rate. FRs below 10 Hz will yield sharp performance degradations, in terms of both response time and heading accuracy.
37	Van Erp & Padmos (2003)	**3**, 5, 10, 30 Hz	Perception- Speed & Distance Estimation	Accuracy	No effects were observed.
38	Vitkovitch & Barber (1994)	**12.5**, **16.7**, 25 Hz	Target recognition- lip reading	Accuracy	Performance improved when FR was increased. 16.7 Hz may be adequate for recognition tasks of this nature.
38	Vitkovitch & Barber (1996, Experiment 1)	8.3, **12.5**, **16.7**, 25 Hz	Target recognition- lip reading	Accuracy	Accuracy significantly improved from 53% to 69% correct when FRs were increased from 8.3 Hz to 25 Hz. The change from 8.3 Hz to 16.7 Hz was also significant (52 % to 61% accuracy).
39	Vitkovitch & Barber (1996, Experiment 2)	**8.3**, **12.5**, and 25 Hz	Target recognition- lip reading	Accuracy	FRs higher than 8.3 Hz are necessary for lip reading, with 16.7 Hz being adequate.
40	Whiting et al. (1991)	0, 2, 4, **8**, **16**, and 32 Hz	Target detection	Accuracy	Correct detection decreased as FR decreased. 16 Hz may be the lowest acceptable FR.
41	Williams et al. (1997)	**2**, **5**, 10, 15, and 30 Hz	Target recognition- speech reading	Accuracy	5 Hz is considered to be the minimum requirement for continuous speech reading presentation.

Appendix C. Summary of FR Effects on Subjective Assessment

Note: FR values in Red signify the FR levels where human performance starts to significantly degrade. FR values in Blue signify the lowest FR levels where participants perform normally.

Study No.	Author(s) and Date	FR Manipulation	Task Type	Measures	Findings
42	Apeteker et al. (1995)	5, **10**, **15** Hz	Viewing video clips	Watchability QoS	15 Hz considered "just acceptable" for watchability.
43	Chen (2003)	**0.2** & **15** Hz, , variable (motion-sensitive)	Conversational behavior	Perceived engagement/ enjoyment	FR of 1 new image per 5 seconds is considered acceptable for engagement and enjoyment in video-mediated conversation, but "ineffective" for perceiving hand movements; 15 Hz considered to be useful.
44	French et al. (2003)	**2**, **4**, 8, and 16 Hz	Teleoperating ground robots	Perceived workload	FR of 2 Hz is associated with significantly greater workload
45	Ghinea & Chen (2003)	**5**, 15, 25 Hz	Information assimilation	QoP	Information assimilation and enjoyment can occur for films presented at 5 Hz.
46	Ghinea & Thomas (1998)	**5**, 15, 25 Hz	Information assimilation	QoP	5 Hz can impair satisfaction; 5 Hz may be acceptable in terms of watchability for high action and low resolution video.
47	Gulliver & Ghinea (2004, b, c, & d)	**5**, **15**, and 25 Hz	Information assimilation	QoP	Low FR of 5 Hz has no effect on information assimilation. Level of enjoyment and level of quality are impaired when reducing FR from 15 to 5 Hz. Thus, 15 Hz may be the critical value for QoP.
48	Gulliver, Serif, & Ghinea, (2004)	**5**, 15, 25 Hz	Information assimilation	QoP	Low FR of 5 Hz has no effect on enjoyment
49	Masry & Hemami (2001)	**10**, 30 Hz	Viewing motion clips	Perceived quality (lower motion clips)	Perceived quality can be content dependent. 10 Hz is acceptable for higher action sequences, but not lower motion clips.
50	Masry & Hemami (2001)	**10**, 30 Hz	Viewing motion clips	Perceived quality (higher action sequences)	Perceived quality can be content dependent. 10 Hz is acceptable for higher action sequences, but not lower motion clips.
51	McCarthy et al. (2004, Experiment 1)	**6**, 10, 12, 15, 18, 20, 24 Hz	Viewing video on desktop display	Visual acceptability (subjective) Proportion of eye movements	At 6 Hz, desktop quality was acceptable 80% of the time.
52	McCarthy et al. (2004, Experiment 2)	6, **10**, **12**, 15, 18, 20, 24 Hz	Viewing video on palmtop display	Visual acceptability (subjective)	Critical value for FR in the palmtop is 12 Hz, but 6 Hz is acceptable 50% of the time.
53	Meehan et al. (2002)	**10**, **15**, 20, and 30 Hz	Placement task	Physiological Subjective presence	Lower FRs can impair performance and feelings of presence; 10 Hz causes subjective discomfort. The increase in heart rate was greater at 10 Hz than at 15 Hz, indicating higher stress at 10 Hz.
54	Van Breda et al. (2005)	**3**, 10, and **30** Hz	Viewing 2-D vs. 3-D maps	Subjective effort rating	Greater perceived effort associated with 3 Hz; positive effect of 3-D map was largest when FR was lowest
55	Wilson & Sasse (2000)	**5** and 25 Hz	Viewing video	Subjective quality rating	5 Hz is acceptable for subjective quality

56	Wilson & Sasse (2000)	**5** and **25** Hz	Viewing video	Physiological measure (stress)	5 Hz caused greater stress (as evidenced by physiological measures)
42	Apeteker et al. (1995)	5, **10**, **15** Hz	Viewing video clips	Watchability QoS	15 Hz considered “just acceptable” for watchability.
43	Chen (2003)	**0.2** & **15** Hz, , variable (motion-sensitive)	Conversational behavior	Perceived engagement/ enjoyment	FR of 1 new image per 5 seconds is considered acceptable for engagement and enjoyment in video-mediated conversation, but “ineffective” for perceiving hand movements; 15 Hz considered to be useful.
44	French et al. (2003)	**2**, **4**, 8, and 16 Hz	Teleoperating ground robots	Perceived workload	FR of 2 Hz is associated with significantly greater workload
45	Ghinea & Chen (2003)	**5**, 15, 25 Hz	Information assimilation	QoP	Information assimilation and enjoyment can occur for films presented at 5 Hz.
46	Ghinea & Thomas (1998)	**5**, 15, 25 Hz	Information assimilation	QoP	5 Hz can impair satisfaction; 5 Hz may be acceptable in terms of watchability for high action and low resolution video.
47	Gulliver & Ghinea (2004, b, c, & d)	**5**, **15**, and 25 Hz	Information assimilation	QoP	Low FR of 5 Hz has no effect on information assimilation. Level of enjoyment and level of quality are impaired when reducing FR from 15 to 5 Hz. Thus, 15 Hz may be the critical value for QoP.
48	Gulliver, Serif, & Ghinea, (2004)	**5**, 15, 25 Hz	Information assimilation	QoP	Low FR of 5 Hz has no effect on enjoyment

Glossary of Acronyms

2-D	two-dimensional
3-D	three-dimensional
AR	augmented reality
FCS	Future Combat System
FR	frame rate
GL	gray scale level
HMD	head-mounted display
LOD	level of detail
MRI	magnetic resonance imaging
MSR	mean system responsiveness
QoP	quality of perception
QoS	quality of service
rms	root mean square
SD	standard deviation
SDSR	standard deviation of system responsiveness
SL	system latency
SR	system responsiveness
UGV	unmanned ground vehicle
VE	virtual environment
VR	virtual reality

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